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ScienceDirect
Procedia Manufacturing 3 (2015) 1335 – 1342
Procedia MANUFACTURING

6th International Conference on Applied Human Factors and Ergonomics (AHFE 2015) and the Affiliated Conferences, AHFE 2015

Defining human failure events for petroleum applications of human reliability analysis

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Abstract

Human failure events (HFEs) are the unit of analysis in human reliability analysis (HRA). HFEs are essentially human errors that have an adverse consequence on system safety. In HRAs in the nuclear power industry, HFEs are typically defined in the probabilistic safety assessment (PSA), staring with possible hardware failures and then identifying opportunities for human action or inaction to affect those failures. In other industries, the HFE may not be predefined in this manner. For example, in the case of some oil and gas applications, the overarching quantitative risk analysis (QRA) does not identify HFEs. As human factors experts perform HRAs, there is difficulty in characterizing human actions in such a way that they represent the right level of analysis suitable for inclusion in the PSA or QRA. This paper provides guidance to help analysts in such a situation. The paper presents seven steps to build suitable HFEs based on an initial human factors task analysis.

Keywords: Human reliability analysis;Human failure event;Task analysis;Petroleum;Guidance

1. Introduction

To be effective, human reliability analysis (HRA) must have clearly defined units of analysis. In the probabilistic safety assessments (PSAs) used in the nuclear power industry, this unit of analysis is defined as the human failure event (HFE). The HFE encompasses any hardware system that can be adversely affected by human action or

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doi:10.1016/j.promfg.2015.07.289

inaction. As noted in [1], HRA methods often lack a consistent level of task decomposition at the HFE modeling phase, which can result in high variability in the resultant human error probabilities (HEPs).The level of task decomposition also affects the dependency between tasks, which may have a further effect in driving the HEP.The issue is not that different HRA methods necessarily produce different results for the same HFE; rather, different HRA methods may decompose the HFE to different levels.Thus, the quantification of the same event may entail different assumptions and, to some extent, different groupings of tasks across HRA methods. In other words, because of a lack of a common task decomposition framework, HRA methods may not be using the same unit of analysis when producing the HEP.

This problem is magnified as HRA methods are generalized from existing nuclear applications to new domains like oil and gas. In the petroleum sector, the quantitative risk analyses (QRAs)—which are related to PSAs—have historically not modeled HFEs. Thus, where practice has given rise to HFEs in PSAs, the HFEs must be defined and inserted into the QRA for many oil and gas applications. The task of performing the HRA resideswith human factors experts, who build the HRA using methods that have not been aligned to the PSA. For example, as noted in [2] and [3] and depicted in Fig. 1, whereas the PSA may look top-down at the subset of hardware failures that feature a human contribution, human factors may look bottom-up at the subset of human activities that result in human errors. The products of these two events—both of which are technically HFEs—may not be identical. To help resolve this issue, this paper provides a simplified guideline to ensure that the human factors expert—using techniques native to the field—will produce a set of HFEs that are compatible with the HFEs that are incorporated in a PSA or QRA. This paper consolidates and builds on HFE modeling insights previously documented in [2-4].

2. A guideline for HRA task decomposition

In order to reconcile the disconnection between human factors analysis and HFEs in practice, this section presents a seven-step guideline for conducting a task analysis that culminates in usable input for HRA in a PSA. The guideline is appropriate for applications such as an HRA in which HFEs have not been predefined as part of the PSA. The guideline references specific methods to use, e.g., the SPAR-H HRA method [5], but the general approach is interchangeable with a variety of alternate methods. The guideline aligns the bottom-up task analysis approach with the top-down PSA approach for defining and analysing HFEs in HRA.

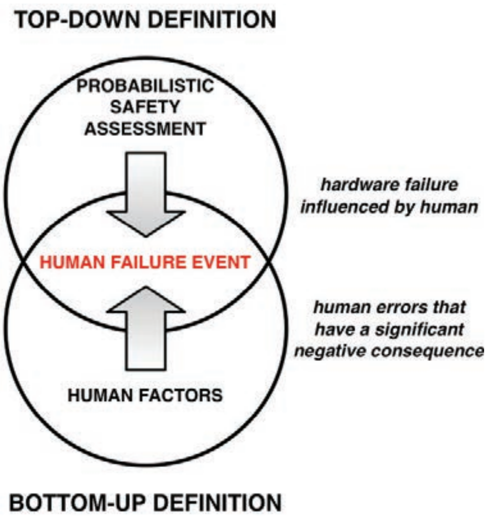

Fig. 1. Two approaches to defining human failure events.

2.1. Step 1: perform task analysis

A task analysis is a description of the steps that are carried out as part of an activity, and it provides a systematic means of organizing information collected around the tasks. The level of detail of a task analysis can vary considerably, although the general guidance is to tailor the level of the analysis to the requirements at hand. For example, a task analysis to support the design of a new system might have a very detailed analysis of ways to improve the design; in contrast, a task analysis to support HRA will tend to be heavily grounded in identifying sources of human error. A task analysis is not strickly speaking a requirement for an HRA. Rather, a task analysis is a way of understanding the activities that are being analyzed and translating these details into the level of detail suitable for the PSA and QRA. The task analysis helps to define the HFE and also helps to identify the human errors that may be present in an activity. The task analysis is also the basis for understanding the impact of specific performance shaping factors (PSFs) and thereby the basis for the quantification in many methods. As such, it is an invaluable stepping stone toward the completed HRA.

Embrey [6] distinguishes between action-oriented and cognitive approaches for task analysis. Action-oriented approaches involve observable behaviors (such as visible tasks), while cognitive approaches look primarily at problem solving and decision making. Tasks may entail taking an action or making a decision, while the steps to support those tasks may involve actions or information gathering (i.e., perceptual tasks).An important consideration is that most actions and decisions are governed by overarching goals. Whether procedurally driven or based on the expertise of the operator, a series of goals guide behavior. Goals are therefore a useful way to group sets of actions together. Also, since the precursors to actions—namely the decisions operators make—are not always readily observable as actions, understanding goals can help the analyst determine what decisions might be necessary for the operators to make. The analyst should ask questions of the operators and other subject matter experts to identify goals as part of data collection for the HRA.

Further, goals are broken down into subgoals or tasks necessary to accomplish the goals. For example, if the high-level goal is to stop a gas leak, subgoals or tasks might include closing a valve and stopping the process that is producing the gas. These subgoals shape the actions the operator takes, including the possible ways to mitigate the problem. Goals are also important to understanding the type of errors that are possible. In the parlance of Reason [7], if the operator has the right understanding of the problem at hand, the errors that might occur would include *slips* (doing the wrong thing despite a good understanding) and *lapses* (failure to do the right thing). If the operator does not have proper understanding of the problem at hand, the potential error would be a *mistake*. Such error taxonomies are helpful to anticipating the types of errors that might occur for different situations.

There are numerous methods for task analysis (e.g., [8]), and a full review is beyond the scope of this paper. Many task analysis methods are simply refinements of basic, established approaches. Still other task analysis methods that were designed for particular human factors applications may not prove suitable for HRA applications. Kirwan [9], in discussing task analysis specifically for HRA, limits his discussion to a handful of methods, but highlights in particular hierarchical task analysis (HTA). HTA is a task analysis method that decomposes tasks hierarchically according to goals at the top level and the tasks at the lower levels that are required to accomplish the goals. This approach is very widely used for both human factors and HRA applications, and it represents a simple yet flexible approach akin to many contemporary simplified HRA methods.

Analysts should not be limited to HTA when other techniques are warranted. For example, [9] specifically mentions tabular task analysis (TTA), which is an extension of HTA that may prove especially effective for cataloging which users are involved in particular tasks, error opportunities for the tasks, etc. This information is represented in a table format. A variant of TTA—operational sequence diagrams—represent similar information graphically. While the many variants on task analysis may provide additional insights to the analyst while completing the HRA, it should be noted that most such techniques add layers of complexity and time onto the analysis. The resources required for such an analysis may be justified, especially in the face of complex, difficult to understand, and highly risk significant activities. Otherwise, the analysts should strive to be efficient in completing the analysis in a cost effective and timely manner. HTA and TTA can help ensure this objective.

Good explanations on how to conduct HTA can be found in any of the various summary articles by Annett published in the early 2000s [10-12]. HTA breaks down a given human-performed task according to goals and subgoals. Typical steps include:

- Align analysis level of decomposition to the purpose of the analysis (e.g., decompose tasks according to the level that human error identification is possible, which serves as the stop rule for the analysis).
- Determine task goals.
- Acquire data to support and document the task decomposition.
- Iterate the task breakdown with subject matter experts until the detail is accurate and sufficient.
- Filter for the most significant operations (e.g., determine that the task has a reasonable probability and consequence of error—otherwise the task should not be considered further in the analysis).
- Identify means to solve identified problems in the task analysis.

For HRA, the HTA needs to decompose to the subgoal/plan level where the analyst can look concretely at opportunities for error. For HRA specific purposes (in contrast to human factors focused on the design of new systems), an analyst would not necessarily need to look at the opportunity to remedy these potential failures, although the analyst should in his or her data collection identify opportunities for recovery from any potential failures.

2.2. Step 2: review the subgoals according to an error taxonomy

The result of the task analysis is a set of goals that cluster sets of actions in the task and a set of subgoals that comprise the individual steps to achieving the goal. Each subgoal may be further subdivided into additional sub-subgoals and so on as necessary to achieve each subgoal. After the completion of the task analysis, the next step is to review the significant subgoals for their potential for human error. A number of error taxonomies exist that support task analysis, e.g., the Systematic Human Error Reduction and Prediction Approach (SHERPA) [13], the Technique for the Retrospective and Predictive Analysis of Cognitive Errors (TRACEr) [14], or even the recent Integrated Decision-tree Human Error Analysis System (IDHEAS) [15]. The SHERPA and TRACEr error mode taxonomies, among numerous others (see [8] for a review), are functionally fairly similar and may be used interchangeably as desired. The TRACEr approach is a bit more complex, featuring a total of eight taxonomies to cover the error context, the production of the error, and the recovery of the error for both predictive and retrospective analysis. In practice, however, TRACEr covers most of the same errors as SHERPA, with the addition of gradations of scale. Whereas SHERPA is relatively absolute in terms of an error occurring or not occurring, TRACEr scales the errors (e.g., too little action or action too long). TRACEr also delineates internal and external error modes, corresponding to cognition (internal) and action (external), although this distinction is implicit in SHERPA.

IDHEAS is actually an HRA method in itself, but it includes a generic psychological taxonomy as part of the method. The taxonomy behind IDHEAS includes a number of cognitive errors but very few action error modes. Whereas it may be easier to identify and catalog action errors in SHERPA, IDHEAS provides a more complete way to identify and catalog cognitive errors. A variant of SHERPA presented for Step 3 essentially aligns SHERPA with IDHEAS.

Table 1 presents the SHERPA taxonomy as an example.This taxonomy provides a concise account of errors of omission and commission. If the bottom-level subgoals do not present a reasonable opportunity for error according to the taxonomy, the analyst should eliminate that overarching task from the analysis. For each subgoal that presents an opportunity for error, the analyst should document the opportunities for recovery from these errors.For typical HRA, it is not necessary to complete the remedy analysis portion of SHERPA (which is useful for improving the process in a design review) but rather to identify actions the system or human might take to recover. The main purpose of the taxonomic review is simply to screen for the reasonableness that an error could occur at the subgoal level.

Table 1. SHERPA error taxonomy.

Action Errors	*Checking Errors*
A1-Operation too long/short	C1-Check omitted
A2-Operation mistimed	C2-Check incomplete
A3-Operation in wrong direction	C3-Right check on wrong object
A4-Operation too little/much	C4-Wrong check on right object
A5-Misalign	C5-Check mistimed
A6-Right operation on wrong object	C6-Wrong check on wrong object
A7-Wrong operation on right object	*Retrieval Errors*
A8-Operation omitted	R1-Information not obtained
A9-Operation incomplete	R2-Wrong information obtained
A10-Wrong operation on wrong object	R3-Information retrieval incomplete
Information Communication Errors	*Selection Errors*
I1-Information not communicated	S1-Selection omitted
I2-Wrong information communicated	S2-Wrong selection made
I3-Information communication incomplete	

2.3. Step 3: identify opportunities for cognitive errors

The SHERPA taxonomy considers mainly action, perceptual, and communication errors. It does not explicitly consider decision errors, although they are implied in some taxonomic items like *A10– Wrong operation on wrong object*. It is recommended that additional Decision items be added to the SHERPA taxonomy to ensure that decision errors are considered. Note that these Decision errors may overlap with other items in the taxonomy. This overlap is inconsequential to the analysis. Suggested decision errors to augment SHERPA's taxonomy are found in Table 2. Note that some taxonomies like TRACEr and IDHEAS may be more complete with regard to cognitive types of errors and may not require this separate guidance in Step 3.

Table 2. Additional cognitive items to augment the SHERPA taxonomy.

Decision Errors
D1-Correct decision based on wrong/ missing information
D2-Incorrect decision based on right information
D3-Incorrect decision based on wrong/ missing information
D4-Failure to make a decision (impasse)

2.4. Step 4: identify risk significant events

Not all errors are risk significant. In order to align the HFE with the level of task decomposition appropriate in PSA or QRA, each identified task should be considered in terms of its opportunity to have an impact on safety, namely to cause or exacerbate a fault in a hardware system. If the task is not connected to a hardware system related to the safety of the facility or process, it can usually be discarded from the analysis. An exception occurs where the safety of individuals (e.g., loss of life) is a modeled risk and is caused by human action or inaction.

2.5. Step 5: synthesize human failure events

Although there remains no authoritative definition of what essential elements comprise the HFEs used in HRAs, for the present purposes consider the HFE to be all actions tied to a particular hardware failure outcome. This means that typically all tasks related to a single hardware system or a single safety outcome should be grouped together as a single HFE. Failure to cluster tasks at the right level of HFE decomposition can result in spurious outcomes as HRA methods are used for human error quantification. HFEs are typically modeled in the PSA or QRA as nodes in fault trees. Depending on the logic used to connect HFEs together, the overall logic model may represent multiplicative (AND gate) or summative (OR gate) functions of the HEPs. If a series of unaggregated tasks from the HTA is treated as individual HFEs, this can have the effect of lowering the overall HEP for AND gates or raising the overall HEP for OR gates.

2.6. Step 6: consider drivers on performance

Many contemporary HRA methods use PSFs to account for the mechanisms that increase or decrease performance. A commonly used PSF-based HRA method is the SPAR-H method [5]. In the SPAR-H method, PSFs are associated with multipliers to raise or lower a default or nominal human error rate. The SPAR-H method is strictly a quantification approach that provides no guidance on defining the HFEs. As such, the method assumes pre-defined HFEs from the PSA, and it is particularly susceptible to generating spurious HEPs when the HFEs are not defined at the appropriate level of decomposition. SPAR-H was originally developed in support of the U.S. Nuclear Regulatory Commission's Accident Sequence Precursor program [16] and is therefore optimized to set the PSF levels retrospectively according to information available in an incident that has already occurred. As such, selecting the PSFlevels prospectively can be challenging. It is important as part of data collection to consider *what-if* scenarios such as “Could time be a factor in overall performance on this task?” or “Could the quality of procedures affect the outcome of this task?”

Per recent step-by-step guidance on SPAR-H [17], it is appropriate to consider only those PSFs that have a dominant effect on the outcome of the HFE. These PSFs should be considered in terms of their positive and negative effect. It is assumed that only the strongest or dominant drivers on performance should be considered in a prospective SPAR-H analysis. Table 3 may help to classify relevant PSFs for each HFE. Each HFE should be walked through with subject matter or process experts according to the SPAR-H PSFs. Any strongly positive or negative drivers should be discussed and used to select an appropriate PSF level. Note that recent work in the petroleum sector has redefined the basic list of SPAR-H PSFs to be more suitable to petroleum HRA [18]. Where appropriate, Table 3 may of course be modified to reflect a different list of PSFs, either through customization of the SPAR-H PSFs or use of another HRA method's PSFs.

Table 3. SPAR-H performance driver table.

Available Time Would you have plenty of time (POSITIVE) or not enough time (NEGATIVE) to complete the tasks?	POSITIVE	NEGATIVE	N/A
Stress Would you feel stressed during the scenario? Would it improve (POSITIVE) or hinder (NEGATIVE) your performance?	POSITIVE	NEGATIVE	N/A
Scenario Complexity Would it be easy (POSITIVE) or difficult (NEGATIVE) to diagnose the situation properly?	POSITIVE	NEGATIVE	N/A
Execution Complexity Would it be easy (POSITIVE) or difficult (NEGATIVE) to carry out the activities in the scenario?	POSITIVE	NEGATIVE	N/A

Experience/Training Would your previous practice and training on this type of scenario improve (POSITIVE) or hinder (NEGATIVE) your performance?	POSITIVE	NEGATIVE	N/A
Procedures Would procedures adequately aid (POSITIVE) or fail to aid (NEGATIVE) the completion of the tasks?	POSITIVE	NEGATIVE	N/A
Human-Machine Interface Is the labeling and organization of information clear and helpful (POSITIVE) or unclear and misleading (NEGATIVE)?	POSITIVE	NEGATIVE	N/A
Fitness for Duty Are there physical factors like being wide awake (POSITIVE) or tired (NEGATIVE) that would affect your performance?	POSITIVE	NEGATIVE	N/A
Work Processes Would organizational factors help (POSITIVE) or get in the way (NEGATIVE) of resolving this scenario?	POSITIVE	NEGATIVE	N/A

2.7. Step 7: perform the human error quantification

Once reasonable errors have been identified, the HFEs have been defined, and the drivers on performance have been predicted, it is finally possible to use this information to complete the human error quantification. Again, using SPAR-H as an example, in the final stage, the analyst would complete the quantification worksheets provided with the method. The SPAR-H process entails:

- Determination if the HFE is *Diagnosis* (cognitively engaging), *Action* (behaviorally based), or both. This determines the starting or nominal HEP (NHEP).
- Assign the PSF levels for the HFE.
- Mathematically compute the basic HEP by taking the product of the nominal HEP and the PSF multipliers that correspond to the PSF assignment levels. If there are both *Diagnosis* and *Action* worksheets, the basic HEP is computed separately for Diagnosis and Action and then added:
- $HEP_{basic} = NHEP_{diagnosis} \times PSFs + NHEP_{action} \times PSFs$ (1)
- Apply a correction factor to ensure no HEP is greater than 1.0.
- Adjust the HEP for dependency between HFEs where appropriate.

It should be remembered that most HFEs include both *Diagnosis* and *Action* tasks [17]. Only dominant drivers on performance should be considered as PSFs, and any assumptions that inform PSF level assignment should be carefully considered and documented. Recovery actions identified as part of the HRA and SHERPA analysis (see Steps 1 and 2 above) should be documented. If recovery actions are modeled separately in the PSA event or fault trees, they should simply be documented as part of the analysis. Where a sequence of successive HFEs is present, dependency should be considered in the analysis per the SPAR-H worksheets. Note that recent guidance [19] has suggested that dependency corrections to the HEP should in many cases be omitted, as it can result in overly conservative values. All such assumptions should be carefully documented to aid in the potential verification and reuse of HRAs. Similar processes can be followed with other HRA methods as preferred. The SPAR-H method is simply presented as a method that aligns well to both HTA and HRA.

3. Discussion

This paper has reviewed the difficulty in defining HFEs for human factors analysts who are completing HRAs where no PSA(or similar model like a QRA) is readily available or the PSAdoes not include HFEs. As HRA is applied to novel domains beyond its traditional use in nuclear power, the completeness of PSAs, particularly with regard to treatment of human actions, will vary considerably. In the absence of predefined HFEs in the PSA, it is important to have a standard, traceable approach to facilitate HRAs that can serve as standalone analyses and can be incorporated into PSAs with the right level of information and granularity. The challenge for the analyst in completing the bottom-up, task analysis driven approach is that there has been no clear process to bridge the task analysis to the completed HRA. This paper has provided initial guidance to help the analyst in such cases. In particular, it is important that the bottom-up defined tasks properly match the granularity required of the HFEs to fit the PSA. It is hoped the guidance in this paper will aid analysts in making this match and in ensuring interanalyst consistency in future HRAs. This guidance should, of course, serve only as a starting point, and analysts should refine and revise it according to their needs.

4. Disclaimer

Idaho National Laboratory (INL) is a multi-program laboratory operated by Battelle Energy Alliance LLC, for the United States Department of Energy under Contract DE-AC07-05ID14517.This work has been carried out as part of The Research Council of Norway project number 220824/E30 “Analysis of human actions as barriers in major accidents in the petroleum industry, applicability of human reliability analysis methods (Petro-HRA)”. Financial and other support from The Research Council of Norway, Statoil ASA and DNV-GL are gratefully acknowledged. This paper represents the opinion of the authors, and does not necessarily reflect any position or policy of the above mentioned organizations. Neither the United States Government, nor any agency thereof, nor any of their employees makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately-owned rights.

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